NASA TECHNICAL MEMORANDUM

NASA TM X-1635

NASA TM X-1635

EFFECT OF VARIABLE STATOR AREA ON PERFORMANCE OF A SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING

II. Stator Detailed Losses With 130 Percent Design Area

by Thomas P. Moffitt, Herman W. Prust, Jr., and Bernard Bider

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1968

NASA TM X-1635

EFFECT OF VARIABLE STATOR AREA ON PERFORMANCE OF A SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING

II. STATOR DETAILED LOSSES WITH 130 PERCENT DESIGN AREA

By Thomas P. Moffitt, Herman W. Prust, Jr., and Bernard Bider

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

The turbine is being investigated at stator area settings of 70, 100, and 130 percent of design. This report presents the experimental and analytically predicted results for the stator having open (130 percent) area setting and compares these results with similar results obtained for the design (100 percent) area setting. The final results are presented in terms of kinetic energy loss coefficients as a function of velocity level. The experimental losses were close to those predicted analytically and indicate a stator efficiency of about 96 percent.

EFFECT OF VARIABLE STATOR AREA ON PERFORMANCE OF A SINGLE-STAGE TURBINE SUITABLE FOR AIR COOLING

II. STATOR DETAILED LOSSES WITH 130 PERCENT DESIGN AREA

by Thomas P. Moffitt, Herman W. Prust, Jr., and Bernard Bider

Lewis Research Center

SUMMARY

As part of a single-stage variable stator area program, an investigation of the kinetic energy loss coefficients of a stator blade row in an open configuration was made. The blading used had desirable cooling features including thick blade sections, blunt leading edges, thick trailing edges with large wedge angles, and a low solidity. In the open configuration, the channel exit orthogonal at the mean section was increased to 130 percent that of the design stator. Experimental and analytical loss coefficients were obtained for the open configuration as a function of velocity and compared to similar values for the design stator.

The overall annular sector kinetic energy loss coefficient of the open stator was determined experimentally to be about 0.04 which is equivalent to an efficiency of 96 percent. This efficiency is about 1/2 percent greater than that predicted analytically. The thick trailing edge, which represented a flow blockage of about 8 percent, contributed about 20 percent of the overall losses.

The experimental overall annular-sector kinetic energy loss coefficient for the open stator was about 0.007 less than that of the design stator, which is in reasonable agreement with the difference of 0.003 predicted from theoretical methods.

A comparison was made of loss coefficients obtained from the open stator tests using measurements with two total pressure probes having different diameter sensing elements and located at slightly different axial positions. This comparison indicated that the loss coefficients obtained from measurements with the probe having very small diameter sensing element very close to the blade trailing edge are higher than actual. These results indicate that the kinetic energy loss coefficients reported for the reference design stator were probably higher than actual because of the type and location of probe used for that investigation.

INTRODUCTION

Advanced aircraft such as the supersonic transport require high performance engines to accomplish their mission goals. To achieve the required high performance, turbine inlet temperatures higher than those currently employed are needed. With available materials, it will be necessary to employ turbine cooling in the engine design to obtain these higher temperatures. In addition, such engine designs must include considerations for maintaining high performance at each of the widely varying off-design modes of operation encountered over the aircraft flight conditions. One method being considered is the use of adjustable turbine stators which permits the turbine to be operated off-design by varying the flow rate at a given turbine pressure ratio as flight conditions vary. When employing this method, it is of course desirable to maintain high turbine efficiency over the required operating range.

In order to better understand the performance characteristics of turbines incorporating variable stator area, one such turbine has been under investigation at the Lewis Research Center. This is a 30-inch tip diameter scale-model turbine, typical of the first stage of a turbine for a supersonic turbojet engine. The blading was designed with large sectional areas and thick leading and trailing edges to allow for both stator and rotor cooling. The design and overall stator performance, the detailed stator performance, and the stage performance of this turbine with design stator flow area setting are presented in references 1 to 3. These performance results are used as the basis of reference for the adjustable stator studies.

To provide equipment for the adjustable stator studies, two additional stator assemblies having flow areas different than design were fabricated. These different flow areas were 70 and 130 percent of design as determined at the exit channel orthogonal at the mean blade section. Both cold-air stator tests and cold-air stage performance tests were conducted for each stator assembly. The overall stator test results for the 130 percent areas are presented and compared to the design stator area tests in reference 4. The subject report presents detailed experimental and analytically predicted performance results including kinetic energy loss coefficients for the 130 percent flow area stator. In addition, kinetic energy loss coefficients for this stator, which is designated hereafter as the "subject open stator," are also compared to those determined for the "reference design stator" reported in reference 2.

To obtain experimental data, annular surveys were made close to the blade trailing edge for a range of ideal after-mix critical velocity ratios from about 0.5 to 0.9. The calculation procedures used for computing the results are from reference 2. Final results are presented in terms of kinetic energy loss coefficients as a function of velocity level. (Efficiency, in terms of kinetic energy, may be obtained by subtracting this coefficient from unity.)

SYMBOLS

$\bar{e}$ kinetic energy loss coefficient

p pressure, lb/ft^2 (N/m^2)

V absolute gas velocity, ft/sec (m/sec)

α_s blade stagger angle measured from axial direction, deg

δ^* displacement thickness parameter

θ^* momentum thickness parameter

Subscripts:

cr conditions at Mach 1

d station downstream used for set point

i ideal conditions corresponding to isentropic process at blade mean section

m mean blade section

0 station upstream of blade row

1 station at stator throat

2 station just downstream of stator trailing edge

2a station just inside stator trailing edge

3 station after complete mixing occurs

3d three-dimensional or annular-sector

Superscript:

' total state

APPARATUS

As indicated in the INTRODUCTION, the setting of the open stator was determined by increasing the channel exit orthogonal at the mean section to a value 30 percent greater than that of the reference design stator. Figure 1 presents the relative blade positions at the mean section for both stators oriented about the center of the trailing edges, thereby maintaining radial trailing edges desirable for stator exit surveys. The associated stagger angle α_s was decreased from 41.03° to 32.59°, a change of 8.44°. This change in angle setting was of course constant radially and resulted in an increase at the hub and tip station exit orthogonals of 35 and 26 percent, respectively.

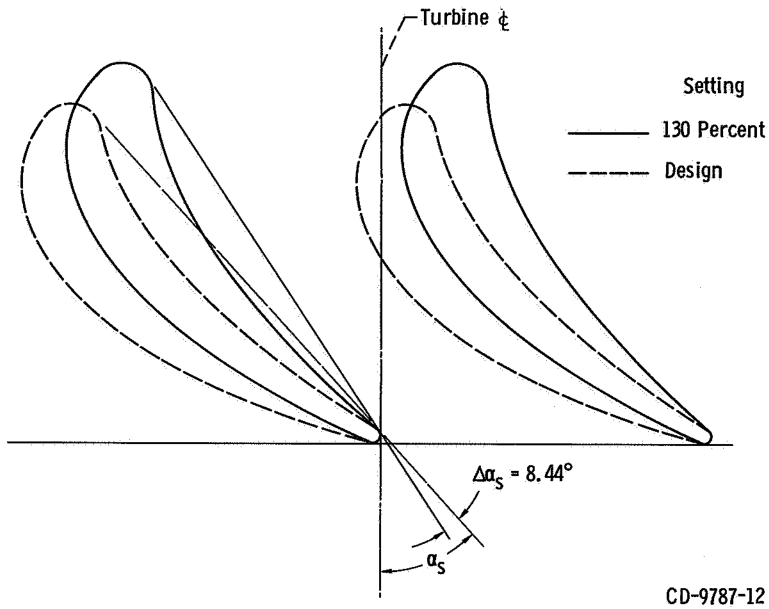


Figure 1. - Stator blade orientation.

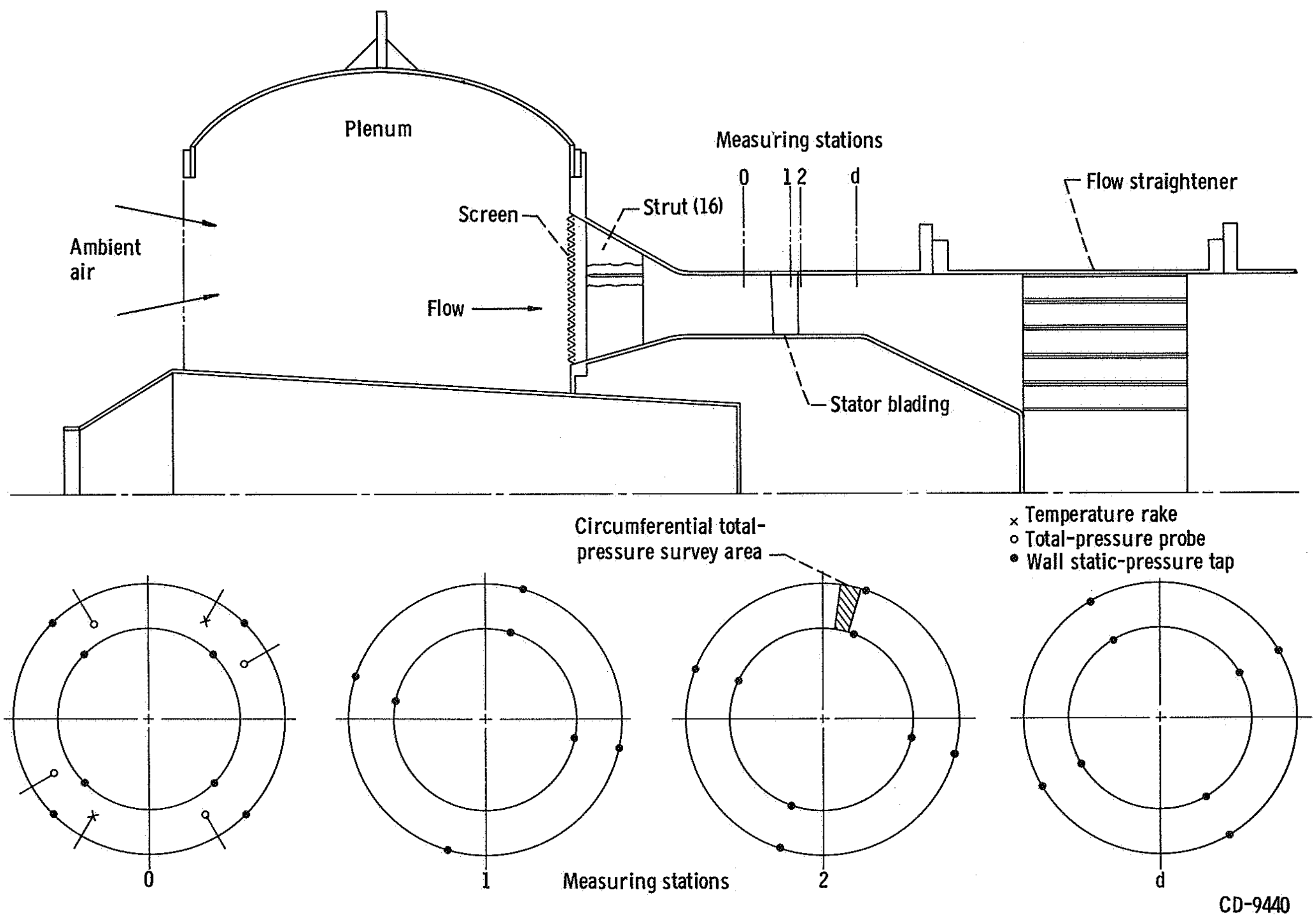


Figure 2. - Schematic diagram of turbine stator assembly and instrumentation (looking upstream).

The test facility that incorporated the subject open stator assembly was the same as that described in reference 2. A cross-sectional schematic of the test facility is shown in figure 2.

INSTRUMENTATION

The instrumentation used for obtaining the reported results was the same as that described for the reference design stator survey tests (ref. 2) except for the survey probe and the addition of several static taps at station 2 (see fig. 3). A brief description of the instrumentation is given for completeness, together with a description of the change in survey probe design and the location of the additional pressure taps.

Pressure and Temperature Measurements

Total-pressure, static-pressure, and temperature measurements were made in the axial-circumferential locations shown in figure 2. The inlet measuring station (station 0) was located one blade chord upstream of the stator blades. Air-inlet temperature was measured by the use of two diametrically opposed rakes, each with five copper-constantan thermocouples, located radially on centers of equal annular areas. Four Kiel-type total-pressure probes were used to measure inlet total pressure. In addition, four static-pressure taps were located on both the inner and outer walls around the annulus at the inlet measuring station. Similar static-pressure taps were provided at the stator throat and exit (stations 1 and 2), respectively (see figs. 2 and 3) as well as the downstream measuring station (station d) located about $2\frac{1}{2}$ blade chords behind the blade. At station 2, in the survey area, three additional static-pressure taps were located on both the inner and outer walls as shown in figure 3.

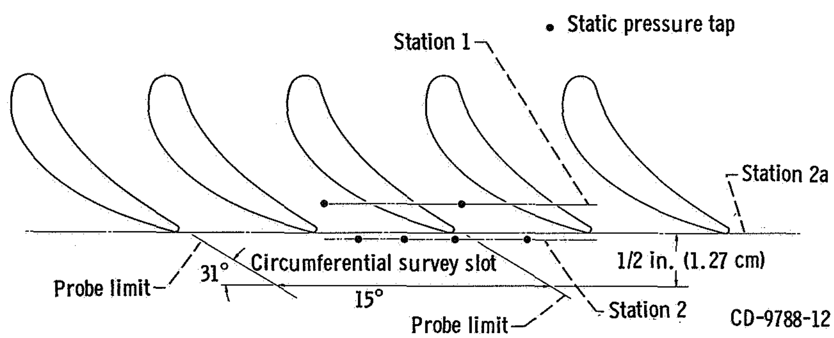
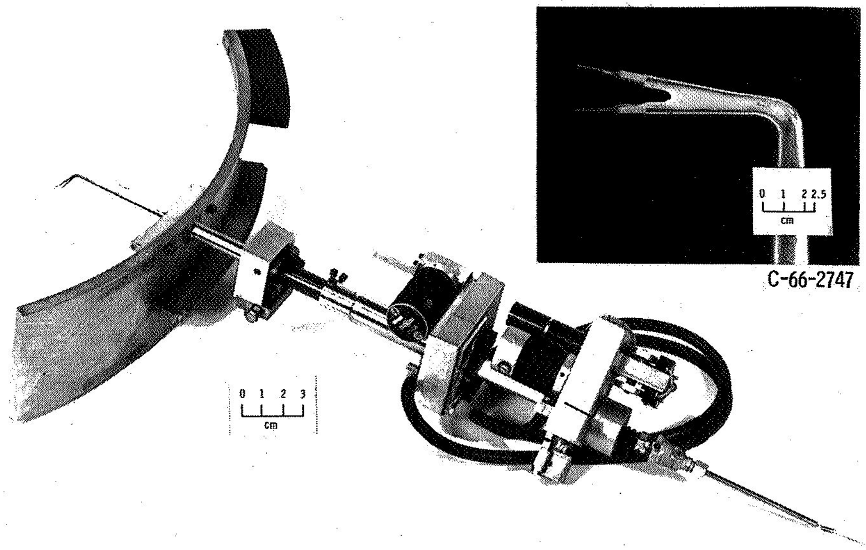
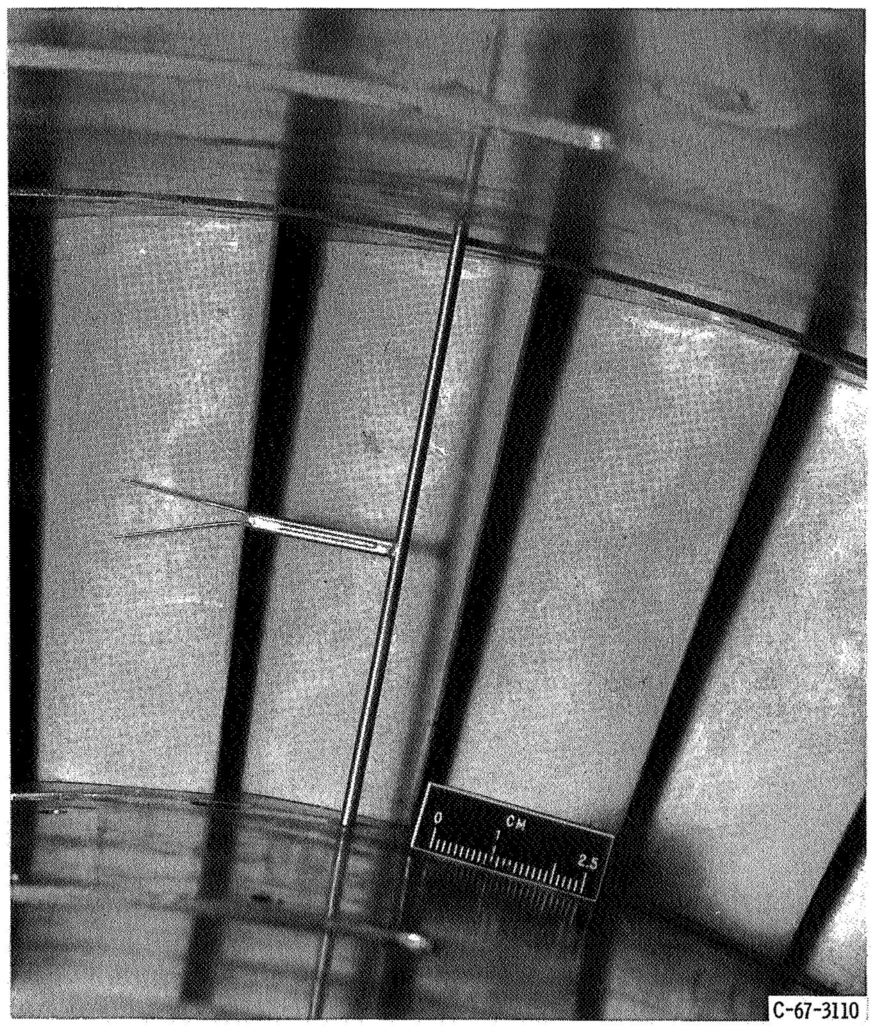


Figure 3. - Schematic of circumferential survey probe travel and approximate location of static pressure taps.



(a) Original probe used for reference design stator testing. C-66-2250



(b) Modified probe used for subject open stator tests.

Figure 4. - Photograph of total-pressure survey equipment.

Modification of Survey Probe

The original probe, actuator, and saddle assembly used for the reference design stator testing (ref. 2) is shown in figure 4(a). The support stem for this probe was tapered radially from 1/4 to 1/8 inch (0.64 to 0.32 cm) normal to the direction of flow over the required radial length. Two tubes were required in order to obtain measurements at the inner and outer walls. The sensing end of both tubes was constructed of 0.012-inch (0.030-cm) tubing with a 0.006-inch (0.015-cm) inside diameter.

A modified probe is shown in figure 4(b) before trimming the ends of the sensing tubes to the required length for surveying. The same actuator and outer saddle assembly as used for the original probe, shown in figure 4(a), were used for this probe. However, the support stem for the modified probe was constructed of 0.100-inch (0.254-cm) tubing and passed through an inner wall saddle assembly. This inner assembly was required to prevent excessive deflection of the smaller diameter support stem. The inner wall saddle was supported on bearings at the shaft centerline and was driven to the same circumferential position as the outer wall saddle. In addition, the outer diameter of the probe sensing element was increased to a 0.020-inch (0.051-cm) tube having an inside diameter of 0.015 inch (0.038 cm). The probe was insulated and provided with an electrical signal to locate the probe with respect to the stator inner and outer walls.

It was felt that the modified probe would yield better results than the original probe. The reasons for this are subsequently discussed in the section BASIS OF RESULTS.

TEST PROCEDURE

The same test procedure was followed for the subject open stator investigation as that described in reference 2. Ambient air was used at the inlet of the stator for all tests. The downstream stator blade hub-static pressure at measuring station d (see fig. 2) was maintained constant for each test point to provide inlet-total- to downstream-static-pressure ratios corresponding to hub-downstream critical velocity ratios of 0.5, 0.7, and 0.9. For the subject testing, static pressures in the wake area at the locations described in the INSTRUMENTATION section (see fig. 3) were also measured to better define the flow conditions. At each set point and selected radius, a circumferential total-pressure survey was made with the modified survey probe. These survey measurements were made about 0.010 inch (0.025 cm) downstream of the stator blade trailing edge, over a span limited to about two complete blade wakes (fig. 3). The probe was set at the predetermined average flow angle of about 31° (see fig. 3). In addition, for the purpose of comparing losses obtained with the original and modified survey probes, an annular-sector total-pressure survey was also made with the original probe at a hub-downstream critical velocity ratio of 0.9. A typical trace on an X-Y recorder, obtained using the

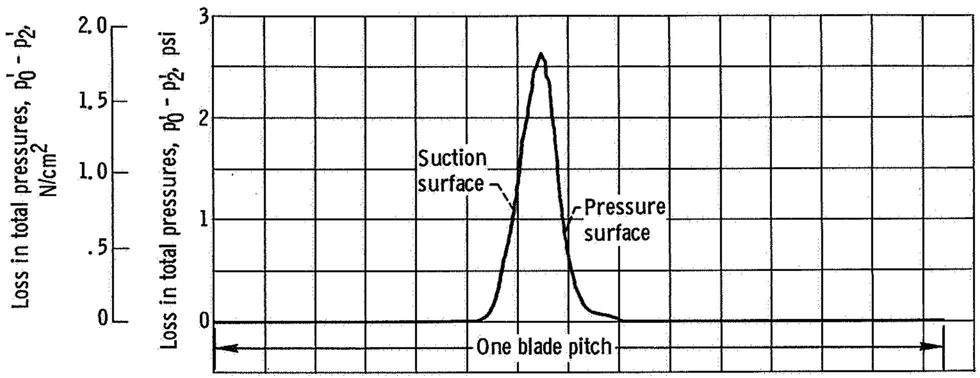


Figure 5. - Typical total-pressure drop data at blade exit at mean section. Ambient inlet conditions.

modified probe, is shown in figure 5 for a survey behind one blade at the mean section. Previous tests and calculations for the reference design stator indicated very close agreement in loss characteristics taken behind two blade wakes. Consequently, all survey data reported herein were taken over a circumferential span of one blade pitch.

BASIS OF RESULTS

A number of exploratory tests were conducted after the results of the reference design stator were published in reference 2. It was generally concluded that the loss results for this stator geometry are sensitive to (1) the type of probe used in terms of the diameter of the sensing element and flow blockage of the support stem, and (2) how close the sensing element was to the trailing edge as it passed circumferentially through the blade wake. This sensitivity is believed to be caused by either one or a combination of the following two effects. First, local flow around the thick trailing edge could result in flow angles relative to the probe that are greater than the angle sensitivity of a small diameter probe sensing element that is very close to the blade. This, then, would result in a measurement of local total pressures less than actual and yield apparent losses that are larger than the actual losses. Secondly, large static-pressure gradients could exist in the wake area close to the blade trailing edge as a result of the fluid near the blade surface diffusing rapidly into a region of low flow at the trailing edge, and the reexpanding to free stream conditions. This would then result in the use of smaller than actual values for static pressures in the wake area close to the blade and yield larger than actual losses.

In an effort to confirm these effects, as well as to try to reduce the probe stem blockage discussed in reference 2, a modified probe as described in the INSTRUMENTATION section was used. The principal modifications of this probe were (1) increased diameter of the sensing element and (2) reduced support stem diameter. This probe, as well as a probe of the original type, was then used to obtain annular-sector total-pressure loss data for the subject open stator at a hub-downstream critical velocity ratio setting of 0.9. For these tests, the end of the sensing element of the original probe was located a few thousandths of an inch from the blade trailing edge to correspond to the location of the same type probe when testing the reference design stator. For the modified probe testing, the end of the sensing element was located slightly farther downstream in an effort to reduce the effect on loss measurements of expected large variations in flow angle and static pressure closer to the trailing edge. For the subject testing, static pressures in the wake area at the locations described in the INSTRUMENTATION section (see fig. 3) were also measured to better define the flow conditions.

A comparison of results for the subject open stator from data measured with the two probes showed a difference in annular sector overall kinetic energy loss coefficients of about 0.01, the loss using data from the original type probe being higher. It, therefore, appears that for this type of blading, the losses obtained using data measured with a probe having too small a diameter sensing element too close to the trailing edge are erroneously high. In addition, since the loss coefficients reported for the design setting stator in reference 2 are based on measurements corresponding to those taken for the subject stator with the original type probe, it appears that these coefficients are also larger than actual.

A comparison of the wall-static pressures in the wake area with the static pressures at midchannel also showed the static pressures in the wake area to be substantially (about 10 percent) larger than those in the center of the passage, indicating that significant diffusion does exist in the wake area.

In view of the foregoing discussion, the results for the subject open stator tests, unless noted otherwise, are presented for data obtained using the modified survey probe.

RESULTS AND DISCUSSION

Experimental and analytical loss coefficients were obtained for the subject open configuration as a function of velocity and compared to similar values for the reference design stator. The results are presented in three sections. The first section presents the experimental results of the subject open stator. The second compares the experimental results with those predicted analytically for the subject open stator. Finally, the third section compares both the analytically predicted results and the experimental results of the subject open stator with those obtained for the reference design stator presented in reference 2.

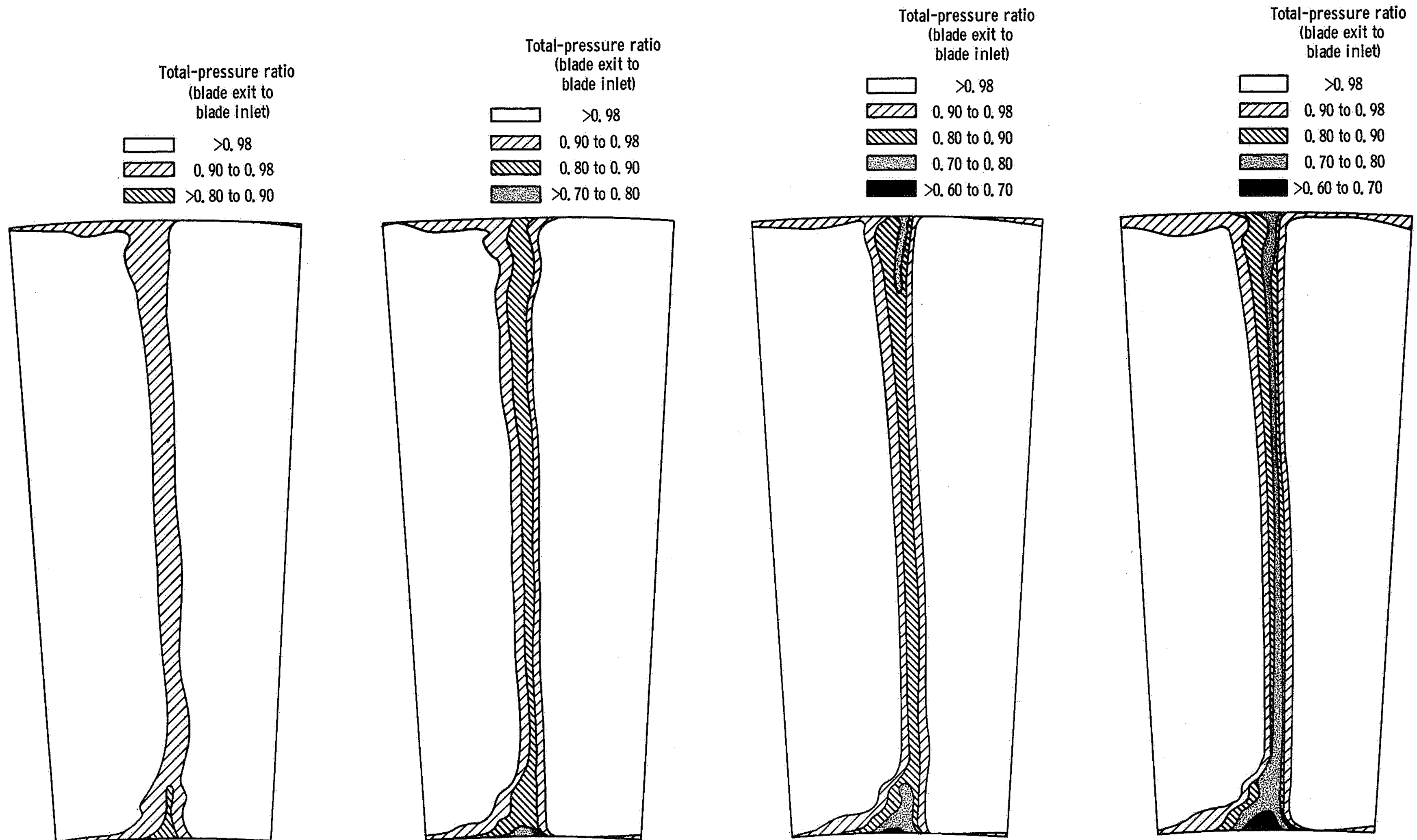
Experimental Results

The experimental results of the subject open stator includes contours of total pressure ratio from annular surveys, variations in loss parameters with radius, blade surface losses at three radial locations, blade trailing edge loss at the mean section, and a summation of mean and annular sector kinetic energy loss coefficients. The kinetic energy loss coefficient $\bar{e}$ expresses the loss in kinetic energy as a decimal part of the ideal kinetic energy of the actual flow at the station under consideration. Efficiency, on a kinetic energy basis, may be obtained by subtracting this coefficient from unity.

Total-pressure ratio and boundary layer parameters. - The contour plots of total-pressure ratio across the blade row p_2'/p_0' are shown in figure 6 for the range of ideal after-mix critical velocity ratios $\left(V/V_{cr}\right)_{i,m,3}$ investigated. Although such plots do not give quantitative losses as a percentage of ideal kinetic energy, the results shown indicate good blade performance as a function of both radius and critical velocity ratio level. There is a buildup of losses at both the hub and tip region where there is a meeting of low momentum fluid due to friction on both the blade surface and the end walls. There are no large cores of high loss fluid, which indicates attached flow at the blade trailing edge and a lack of appreciable movements of secondary flows.

The radial variations in displacement thickness parameter δ_2^* and momentum thickness parameter θ_2^* at the blade outlet as a function of critical velocity ratio are presented in figure 7. The displacement parameter expresses the loss in flow as a decimal part of the ideal flow without blockage. The momentum parameter expresses the loss in momentum as a decimal part of the momentum of the ideal flow without blockage. The variation in these parameters with radius is an indication of the radial variation in blade performance. The trends of figure 7 are similar at each of the critical velocity ratios investigated. There is the expected buildup of losses at both the hub and tip regions due to the combination of blade surface loss, trailing edge loss, and end wall loss. At radii removed from the end walls by about 0.5 inch (1.27 cm) and more, the trend indicates a gradual increase in loss from hub to tip. This could result from a favorable blade loading at the hub section, at a solidity near optimum, with a slight decrease in performance as radius increases to the tip region, where the solidity is lower. It is also noted from figure 7 that the mean section losses are about the average of the losses occurring on the blade surface at radii removed from the end walls by more than about 0.5 inch (1.27 cm). The effect of this will be discussed in the section Comparison of Experimental and Analytical Results.

Blade surface and trailing edge losses. - The experimental surveys taken at station 2 (see fig. 3) include blade trailing edge losses. To exclude trailing edge loss from the measurements, an extended probe of the modified type described in the section



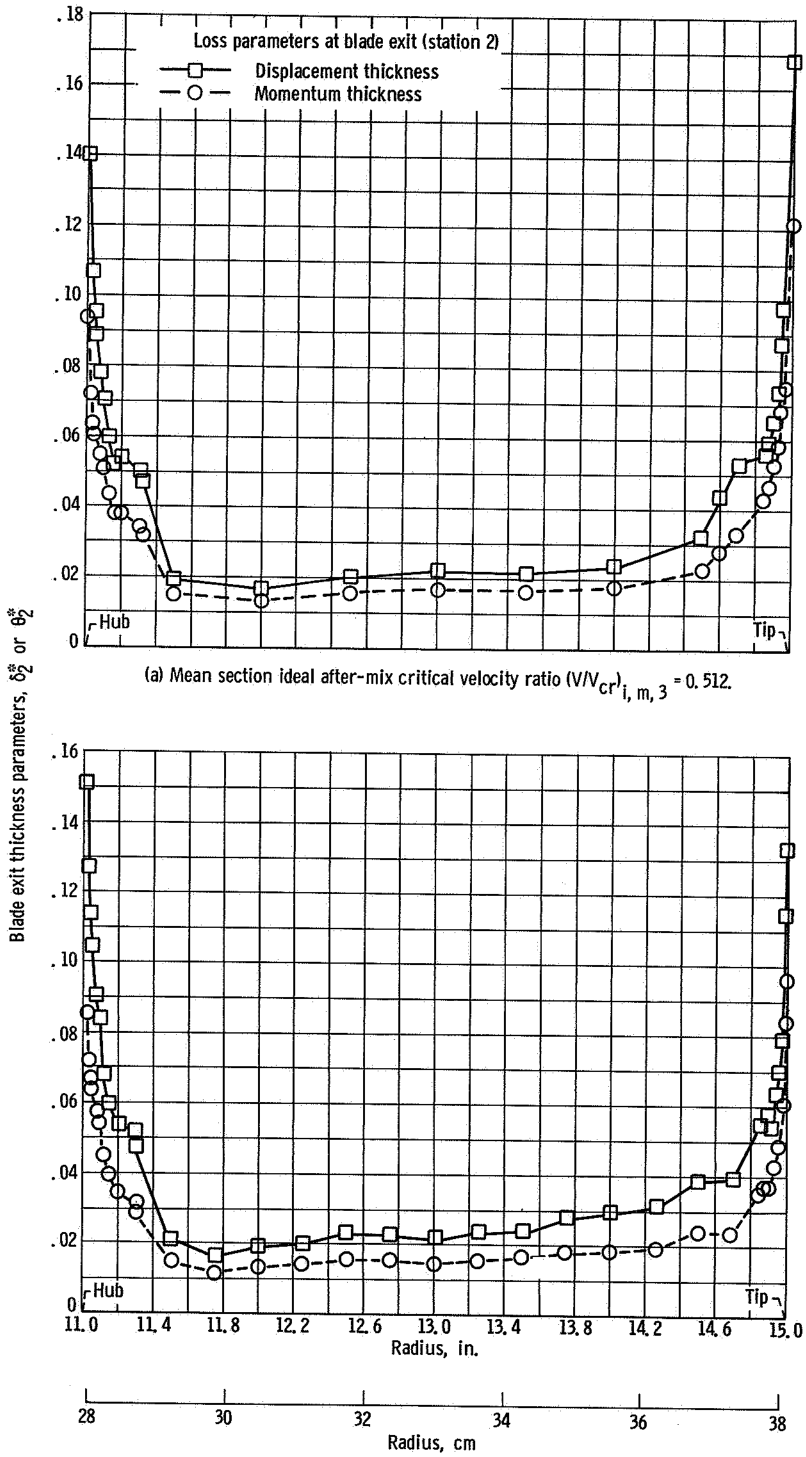
(a) Ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.512$.

(b) Ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.671$.

(c) Ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.823$.

(d) Ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.859$.

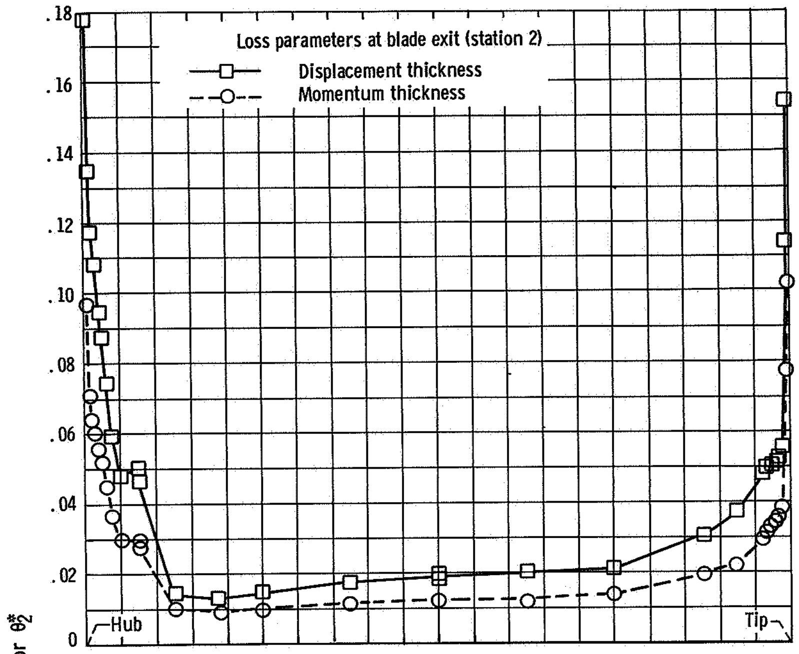
Figure 6. - Contours of total-pressure ratio from annular surveys.



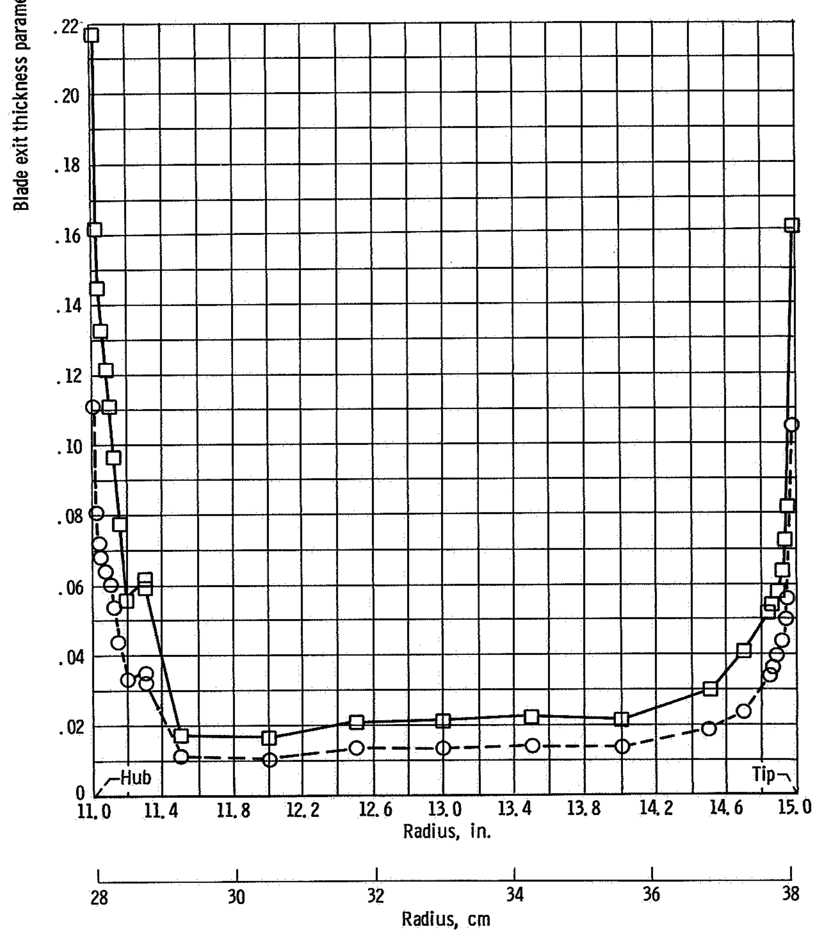
(a) Mean section ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.512$.

(b) Mean section ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.671$.

Figure 7. - Variation in blade exit thickness parameters with radius.



(c) Mean section ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.823$.



(d) Mean section ideal after-mix critical velocity ratio $(V/V_{cr})_{i,m,3} = 0.859$.

Figure 7. - Concluded.

INSTRUMENTATION was used to survey inside the blade trailing edge at station 2a (fig. 3). Circumferential surveys were taken at 12-, 13- (mean section), and 14-inch (30.5-, 33.0-, and 35.6-cm) radial locations. The resulting kinetic energy loss coefficients $\bar{e}_{2a}$ are shown in figure 8 as a function of velocity level. These coefficients represent the loss in kinetic energy due to friction on the blade surfaces and do not include the trailing edge losses. Also shown in the figure are the corresponding losses $\bar{e}_{2,m}$ calculated from circumferential surveys at the mean section blade outlet. The difference between the two curves is an indication of the amount of trailing edge losses occurring at the mean section as determined by experimentation.

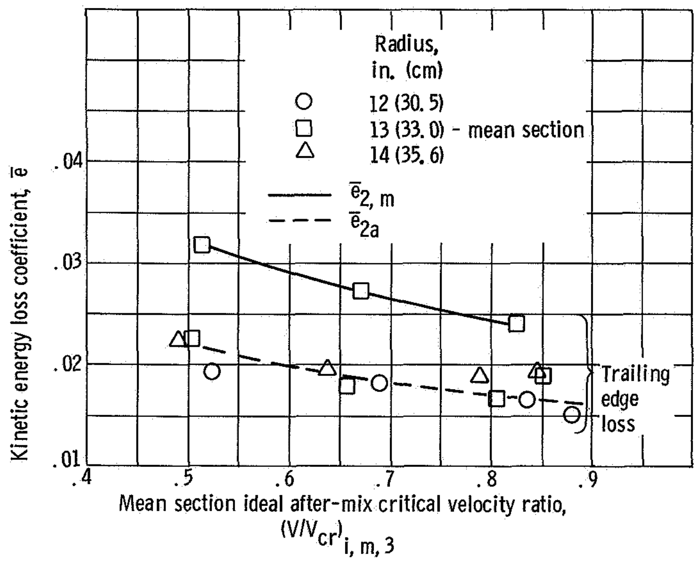


Figure 8. - Loss in kinetic energy due to blade trailing edge thickness.

The trend of the lower curve of figure 8 indicates a decrease in loss coefficient of about 0.006 as critical velocity ratio increases from about 0.5 to 0.9. Referring to the data points at the 12-, 13-, and 14-inch (30.5-, 33.0-, and 35.6-cm) radial positions shows that blade surface losses are fairly constant over the middle 2-inch (5.08-cm) span of the blade and amount to about a 2-percent loss in available kinetic energy.

The trailing edge loss (fig. 8) is noted to represent an average of about 0.8 percent of the available kinetic energy. Although the absolute magnitude of losses measured are small and the scatter between measurements is relatively large, the results of figure 8 are believed to give an indication of the effect of thick trailing edges on blade performance. For the subject blading, the thickness of the trailing edge (0.070-in.-diam. (0.178-cm-diam.)) represents about 8 percent of the free stream exit flow area. However, the indicated loss of the trailing edge is noted to be about one-third as large as that resulting from blade surface frictional losses up to the trailing edge.

Annular-sector losses. - The variation in annular-sector (3d) kinetic energy loss coefficients with critical velocity ratio is shown and compared with mean section kinetic energy loss coefficients in figure 9. Four curves are presented. The lower curve represents the blade surface loss $\bar{e}_{2a,m}$ measured with the extended probe inside the trailing edge at the mean section (13-in.-rad. data of fig. 8). The next higher curve $\bar{e}_{2,m}$ is the same as the upper curve of figure 8 and includes both blade surface plus trailing edge losses at the mean section. The third curve from the bottom $\bar{e}_{2,3d}$ was determined from the annular-sector surveys at station 2 and include, in addition to $\bar{e}_{2,m}$, the three-dimensional (3d) effect of both end wall losses and any variation in blade surface loss from that occurring at the mean section. Finally, the upper curve shows the overall stator loss in terms of the after-mix annular-sector kinetic energy loss coefficient $\bar{e}_{3,3d}$ and results from mixing loss being added to $\bar{e}_{2,3d}$.

Figure 9 indicates total blade row losses from about $3\frac{1}{2}$ to $4\frac{1}{2}$ percent of available kinetic energy, with a slight decrease in loss with increasing velocity. The breakdown in individual losses may be obtained by relating the bottom curve and the differences of the remaining curves to the total loss. Assuming the losses at the mean section to be representative of the losses along the length of the blade, the approximate loss breakdown is as follows: blade surface friction loss, 50 percent; trailing edge loss, 20 percent; end wall loss, 20 percent; and mixing loss, 10 percent. Although the absolute level of total losses is low, it is interesting to note that the trailing edge, which represents about 8 percent of the flow area, contributes about 20 percent of the total losses.

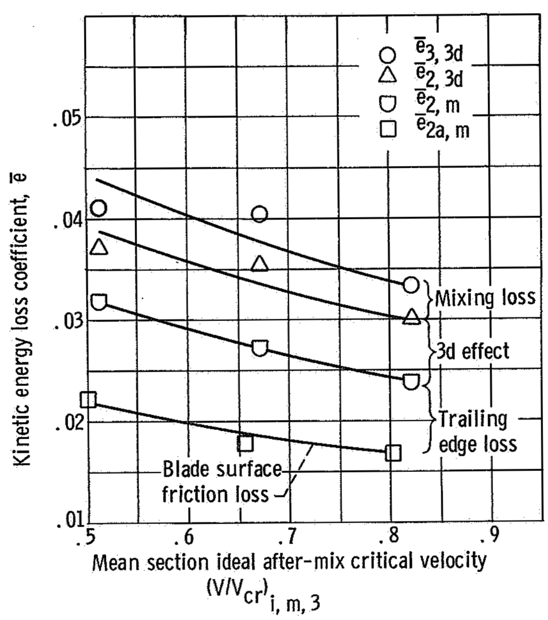


Figure 9. - Variation of loss coefficients with velocity.

Comparison of Experimental and Analytical Results

The blade row losses were analytically predicted in the same manner as described in reference 2 for the design stator. The theory used as a guide was obtained from references 5 to 8. The results are presented in figure 10 for a value of ideal aftermix critical velocity ratio of 0.76. As evident, figure 10 is a repeat of figure 9 (experimental results) with corresponding analytical values inserted as solid data points for comparison.

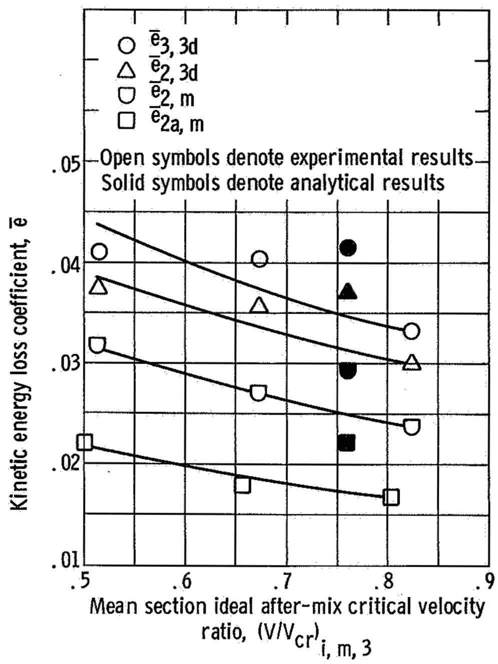


Figure 10. - Comparison of analytical predicted loss coefficients with experimental results.

It is noted from figure 10 that the predicted overall loss ($\bar{e}_{3,3d} = 0.041$) was about 0.006 larger than measured. The predicted and measured values of the trailing edge losses, the end wall losses and the mixing losses all agree very closely. Therefore, this difference in overall loss (0.006) appears to be wholly attributable to blade surface frictional losses up to the trailing edge at the mean section $\bar{e}_{2a,m}$. From this it can be concluded that the mean section blade surface loss $\bar{e}_{2a,m}$ was representative of the losses of the entire blade span and end walls as assumed in the theory (ref. 6). This is in agreement with the radial variation in momentum thickness parameter θ_2^* from figure 7 and discussed previously in the section Experimental Results.

The reason that the measured loss inside the blade trailing edge is somewhat less than predicted is not known. One contributing factor could have been the method of extrapolating the drop in total pressure when the survey probe touched the suction and pressure surfaces at station 2a. The probe had an outside diameter of 0.020 inch (0.051 cm), which then required an extrapolation of data for about 0.010 inch (0.025 cm) to each surface.

Comparison With Reference Design Stator

A comparison was made of both analytical and experimental results of the subject open stator with the reference design stator. To be consistent with reference 2, mean section losses, including the trailing edge, and annular-sector after-mix losses are used as the basis of comparison.

Analytically predicted comparison. - The loss coefficients for the reference design stator were taken from figures 10 and 12 of reference 2 at a critical velocity ratio of 0.76 and compared to corresponding coefficients for the subject open stator. The results are given in table I. The major observation from table I is that the overall performance of the stator in terms of loss in kinetic energy would not be expected to appreciably change in opening the stator exit area.

TABLE I. - COMPARISON OF ANALYTIC LOSS COEFFICIENTS

Loss coefficient	Subject open	Reference design
Blade surface (including trailing edge), $\bar{e}_{2,m}$	0.029	0.034
Overall annular sector, $\bar{e}_{3,3d}$	.041	.044

The predicted combination of blade surface and trailing edge losses of the open stator at the mean section $\bar{e}_{2,m}$ is 0.005 less than the design stator loss. The reason for this difference is twofold. First, although the loss buildup on the open blade surface is larger because of larger velocity gradients and higher peak velocities, the ratio of blade area to flow area is smaller. The net result is a decrease in blade loss coefficient inside the trailing edge. Secondly, the trailing edge loss is less for the open stator because of less trailing edge blockage.

The predicted overall loss of the subject open stator $\bar{e}_{3,3d}$ is about 0.003 less than the reference design stator. The difference became smaller mostly because of the open stator having a slightly larger end wall surface than the design stator, and hence higher predicted end wall losses.

Experimental comparison. - A comparison of the experimental results for the subject open and reference design stator are presented in figure 11. The loss coefficients for the reference design stator were taken from figure 9 of reference 2. Since the results for the reference design stator are based on data measured with the original type total-pressure probe, the results shown for the subject stator are also based on measurements with this type probe in order to be as consistent as possible. For the reasons previously discussed, the measured loss coefficients shown are larger than actual. A comparison of loss coefficients $\bar{e}_{3,3d}$ shown in figures 10 and 11 for the subject open stator, obtained from data measured with the two different type probes, indicates that the coefficients for the subject open stator measured with the original type probe are about 0.01 larger than actual.

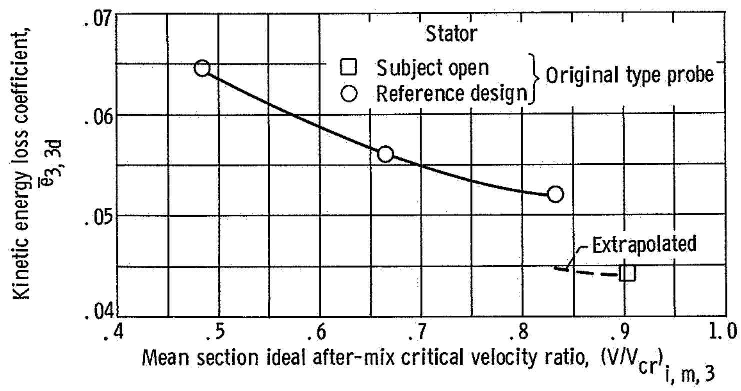


Figure 11. - Comparison of experimental results for subject open stator and reference design stator.

The experimental results presented in figure 11 indicate the overall annular-sector kinetic energy loss coefficient for the subject open stator is about 0.007 less than for the reference design stator. This difference is subject to the previously discussed uncertainties existing because of the location and type of total-pressure probe employed; but, it is in reasonable agreement with the predicted difference of about 0.003.

SUMMARY OF RESULTS

As part of a single-stage variable stator area turbine program, an investigation of the kinetic energy loss coefficients of the stator in an open configuration was made. In this configuration, the channel exit orthogonal at the mean section was increased to 130 percent that of the design area setting. Experimental and analytical loss coefficients were obtained for the subject open configuration as a function of velocity and compared to similar values for the reference design stator. The results are summarized as follows:

1. For the subject open stator configuration, the experimental values of overall annular-sector kinetic energy loss coefficient varied from about 0.045 at a critical velocity ratio of about 0.5 to about 0.035 at a critical velocity ratio of 0.8. Using kinetic energy as the basis, this represents a nozzle efficiency of about 95.5 to 96.5 percent. About 50 percent of the loss resulted from friction on the blade surface up to, but not including the trailing edge. The thick trailing edge (8 percent blockage) constituted about 20 percent of the total loss; the end walls about 20 percent; and about 10 percent mixing loss.

2. Good agreement was obtained between the experimental and analytically predicted results of the subject stator. The predicted overall annular-sector kinetic energy loss coefficient of 0.041 was about 0.006 higher than that measured and was attributable to differences in blade surface losses up to the trailing edge. The blade surface loss at the mean section of the subject blading was concluded to closely represent the losses of the total blade length and end walls as assumed in the prediction method.

3. The experimental overall annular-sector kinetic energy loss coefficient for the subject stator was about 0.007 less than that for the reference design stator. This experimental difference is in reasonable agreement with the analytically predicted difference of 0.003.

4. A comparison of loss coefficients for the subject open stator obtained from measurements with two total-pressure probes having different diameter sensing elements located at slightly different axial positions indicates that the loss coefficients obtained from measurements with a probe having very small diameter very close to the blade trailing edge are about 0.01 higher than actual. This discrepancy in losses appears to result from large variations in flow angle and static pressure in the wake area close to the trailing edge which cause errors in the determination of total-pressure loss and static-pressure conditions. Since the losses for the reference design stator were based on such measurements, it is probable that those reported for that stator were higher than actual.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 6, 1968,
126-15-02-15-22.

REFERENCES

1. Whitney, Warren J.; Szanca, Edward M.; Moffitt, Thomas P.; and Monroe, Daniel E.: Cold-Air Investigation of a Turbine for High-Temperature-Engine Application. I. Turbine Design and Overall Stator Performance. NASA TN D-3751, 1967.
2. Prust, Herman W., Jr.; Schum, Harold J.; and Behning, Frank P.: Cold-Air Investigation of a Turbine for High-Temperature Engine Application. II. Detailed Analytical and Experimental Investigation of Stator Performance. NASA TN D-4418, 1968.
3. Whitney, Warren J.; Szanca, Edward M.; Bider, Bernard; and Monroe, Daniel E.: Cold-Air Investigation of a Turbine for High-Temperature-Engine Application. III - Overall Stage Performance. NASA TN D-4389, 1968.
4. Szanca, Edward M.; Behning, Frank P.; and Schum, Harold J.: Effect of Variable Stator Area on Performance of a Single-Stage Turbine Suitable for Air Cooling. I. Stator Overall Performance With 130-Percent Design Area. NASA TM X-1632, 1968.
5. Stewart, Warner L.: Analysis of Two-Dimensional Compressible-Flow Loss Characteristics Downstream of Turbomachine Blade Rows in Terms of Basic Boundary-Layer Characteristics. NACA TN 3515, 1955.
6. Stewart, Warner L.; Whitney, Warren J.; and Wong, Robert Y.: Use of Mean-Section Boundary-Layer Parameters in Predicting Three-Dimensional Turbine Stator Losses. NACA RM E55L12a, 1956.
7. Whitney, Warren J.; Stewart, Warner L.; and Miser, James W.: Experimental Investigation of Turbine Stator-Blade-Outlet Boundary-Layer Characteristics and a Comparison with Theoretical Results. NACA RM E55K24, 1956.
8. Hoerner, Sighard F.: Fluid-Dynamic Drag. Midland Park, N.J., 1965.

NASA-Langley, 1968 —— 3 E-4416

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546